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ABSTRACT

The flow stress of many materials is a function of the applied strain rate at elevated temperature. The magnitude of this effect is captured by the strain rate sensitivity parameter “*m*”. The strain rate sensitivity of two face-center cubic solid solution alloys that are proposed for use in high temperature heat exchanger or steam generator applications, Alloys 800H and 617, has been determined as a function of temperature over that range of temperatures relevant for these applications. In addition to determining the strain rate sensitivity, it is important for nuclear design within Section III of the ASME Boiler and Pressure Vessel Code to determine temperature below which the flow stress is not affected by the strain rate. This temperature has been determined for both Alloy 800H and Alloy 617. At high temperature the strain rate sensitivity of the two alloys is significant and they have similar *m* values. For Alloy 617 the temperature limit below which little or no strain rate sensitivity is observed is approximately 700°C. For Alloy 800H this temperature is approximately 650°C.

INTRODUCTION

Alloy 617 is a commercial face-center cubic alloy strengthened by solid solution hardening provided by the alloy elements chromium, cobalt and molybdenum as well as by intra- and inter-granular carbide precipitates. High temperature oxidation resistance is derived from the high nickel and chromium content. This alloy was widely investigated in the past for applications in gas cooled reactors for heat exchanger applications for service temperatures up to 950°C.(1) It has also been extensively studied at lower temperatures for steam generator tubing for ultra-supercritical fossil energy generation.

Interest in understanding deformation behavior in this alloy up to 950°C has been rekindled recently as a result of the Next Generation Nuclear Plant (NGNP) project.

Alloy 800H is under consideration for use in the steam generator in some conceptual designs for an NGNP. This alloy is a face-center cubic iron based material with high nickel and chromium content. Unlike Alloy 617 it is approved in the nuclear design section of the ASME boiler and Pressure Vessel Code, but only up to 750°C. There is a proposal moving through the ASME approval process to allow use of 800H up to 850°C. The alloy does not contain some of the solid solution strengthening elements that are present in Alloy 617, principally Co and Mo, and the allowable stresses at 850°C will be very low.

For engineering design it is typically assumed that there is a unique flow stress for a material independent of strain rate below which there is negligible inelastic deformation. At elevated temperatures the flow behavior of Alloy 617 and 800H is highly dependent on strain rate.(2-4) For example at 900°C the flow stress of Alloy 617 increases from 50 MPa at 10^{-6} /s to 250 MPa at 10^{-2} /s.(5) A typical strain rate for a tensile tests used to determine the flow stress is 10^{-3} /s. Thus, strain rate will affect the allowable stress values used in engineering design in the temperature range of interest for hot gas piping and intermediate heat exchanger components. In addition to high strain rate sensitivity, both alloys have also been shown to exhibit significant serrated flow, typically associated with solute pinning, in the temperature ranges of 600-850°C and 500-650°C for Alloy 617 and 800H, respectively.(5) The

magnitude of serrated flow is a function of the strain rate and test temperature.

The flow stress and strain rate are typically related at a constant temperature and strain by the following equation:

$$\sigma = C (\dot{\epsilon})^m \quad (1)$$

where C is a constant, σ is the flow stress, $\dot{\epsilon}$ is the strain rate, and m is the strain rate sensitivity.

There are several ways to determine the value of m .(6) In concept, it is possible to carry out a series of tensile tests with varying strain rates at a series of temperatures. In practice this is rarely done because of the time and number of specimens that would be required. Instead, it is common to carry out strain rate jump tests, where a single specimen is tested at a given strain rate until a steady state flow stress is obtained and then the strain rate is rapidly increased to obtain the flow stress at the next incremental strain rate. The result of such a test is shown in Fig. 1.

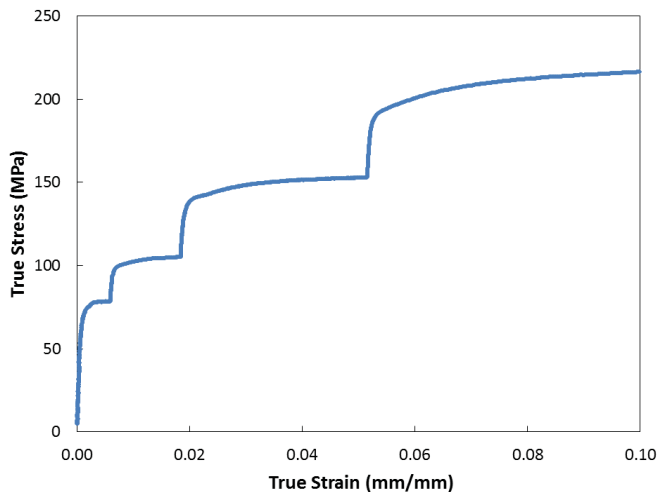


Fig. 1. Strain rate jump test for Alloy 800H at 850°C. Rapid increase in flow stress is associated with strain rate increases of approximately an order of magnitude.

It is also possible to obtain the flow stress over a wide range of strain rates from stress relaxation data.(6) In this test the specimen is loaded in tension to a fixed stress or strain before the specimen extension is fixed. The stress to maintain that fixed strain decays over time at elevated temperature yielding a stress relaxation curve. By fitting a power law expression to the experimental data and taking the derivative of that function the rate of change of stress with time can be determined. Note that rate of change of stress can be converted to a rate of change of strain using Hooke's law with a modulus that is corrected for temperature. A log-log plot of stress and calculated strain rate has a slope that is equal to m . In studies of superplastic aluminum alloys this technique has been shown to

yield strain rate sensitivities that are consistently lower than those from tensile or strain rate jump tests.(6) It appears that this method is inappropriate for predicting the flow stress of a material where the strains are significantly above the yield stress.

In this paper the strain rate sensitivity of Alloys 800H and 617 determined from strain rate jump tests are compared for the temperature range 650 to 1000°C. The relationship of the temperature dependence of the measured strain rate sensitivity to the tensile curves for both alloys is determined. Suggested temperatures below which the tensile properties are essentially independent of the temperature are determined from this analysis.

EXPERIMENTAL PROCEDURE

Elevated temperature tensile properties were measured at 50°C intervals for Alloy 617 and 800H in the temperature range of 650-1000°C and 500-850°C, respectively. All specimens were machined from annealed plate with the long axis of the specimen aligned with the rolling direction. Tensile specimens conformed to ASTM E21, with a 6.35 mm diameter reduced section and a reduced section length of 32mm. Room temperature tensile tests were also done (ASTM E8). Testing was performed at an initial strain rate of 1.6×10^{-4} /s.

Strain rate jump tests were conducted in displacement control at temperatures of 650-950°C using the tensile specimens described above. In displacement control the actuator motion is not directly related to the strain rate. This control mode eliminates extensometer feedback to the servohydraulic frame. However the desired strain rate is achieved by estimating the proper displacement rate and the actual strain rate is calculated after the tests. An example is shown in Fig. 2 for an 800°C test of Alloy 617 where the strain is plotted as a function of time and the strain rate jumps are indicated by a change in slope and delineated by a symbol for clarity. The strain rate is initially slower than intended because of the difficulty controlling at such low strain rates, so the first symbol shows the point from which the strain rate preceding the first jump was calculated.

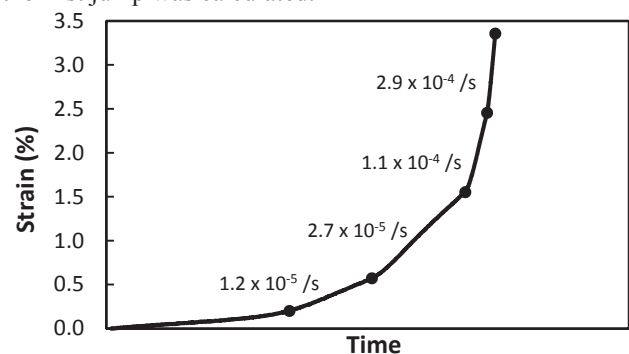


Fig. 2. Loading rate for the Alloy 617 800°C displacement controlled strain rate jump test showing calculated strain rates.

The numerical value of the strain rate sensitivity exponent, m , defined in Equation 1 is determined from the instantaneous change in stress associated with an instantaneous change in strain rate, where subscripts 1 and 2 indicate values before and after the jump:

$$m = \frac{\log(\frac{\sigma_2}{\sigma_1})}{\log(\frac{\dot{\epsilon}_2}{\dot{\epsilon}_1})} \quad (2)$$

It is typically found that the flow stress requires a finite amount of strain to stabilize after a strain rate jump and a consistent method of determining the parameters for Equation 2 is required. An example of a jump test for Alloy 800H at 700°C is shown in Fig. 3. The stress σ_1 , immediately prior to the jump, is determined from the digital data represented by red x. A straight line is fit to the flow curve after the strain rate jump and the equation for that line is used to extrapolate to the strain immediately after the strain rate jump and calculate the stress σ_2 indicated by the orange cross. From these numerical values and the strain rates before and after the jump, the value of the strain rate sensitivity exponent, m , can be calculated for each strain rate jump. Note that although in most cases the strain rate sensitivity is positive, i.e., the flow stress increases with increasing strain rate, it is possible for the strain rate sensitivity to be negative (7-9) as in this example at the highest strain rate.

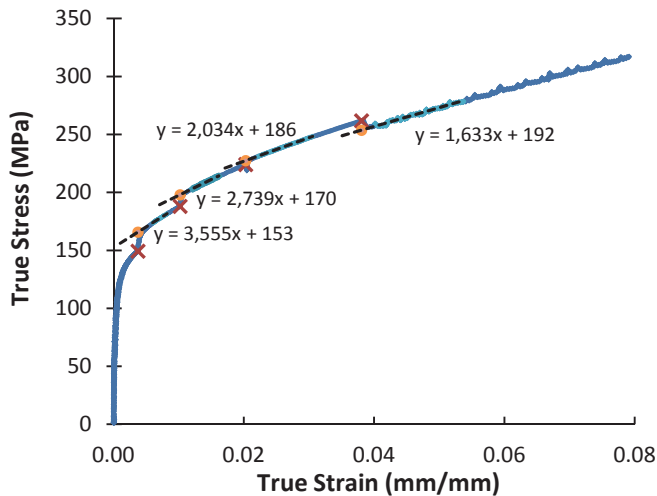


Fig. 3. Strain rate jump test for Alloy 800H at 700°C illustrating how the flow stress is determined before and after the strain rate jump.

RESULTS AND DISCUSSION

Strain rate jump tests for temperatures from 700 to 950°C for Alloy 617 are shown in Fig. 4. It can be seen from the figure that for temperatures from 800°C and above the increments in stress associated with the strain rate jump are of consistent magnitude. At the lower temperatures there is serrated flow, thought to be associated with dynamic strain aging; however there is little evidence of strain rate sensitivity.

Fig. 5 shows a plot of stress as a function of strain rate on a log-log plot from which the numerical values of C and m in Equation 1 can be determined for Alloy 617. It can be seen that the stress exponent is constant for a given temperature in this range for the strain rates examined; however, the magnitude of the exponent increases slightly with increasing temperature. This indicates that Alloy 617 is less strain rate sensitive as the temperature is reduced until, as can be seen visually in Fig. 4, there is essentially no strain rate sensitivity at 700°C. For 700°C and below there is a single flow stress for each temperature that is invariant within the range of strain rates examined here. Above that temperature the flow stress cannot be specified without also specifying the strain rate.

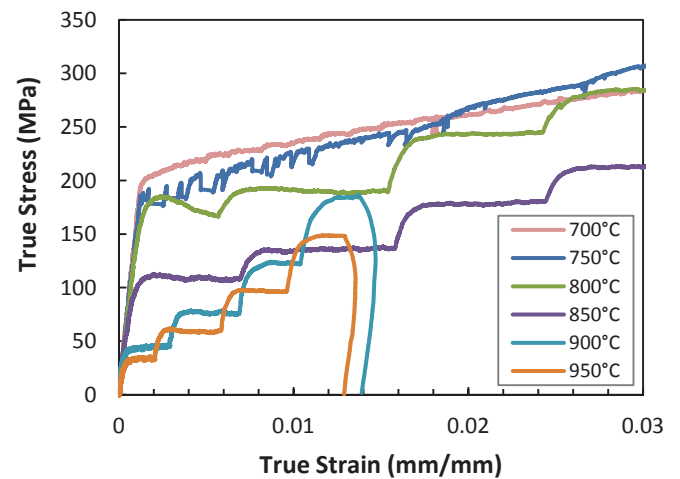


Fig. 4. Strain rate jump tests for Alloy 617 over the range of temperatures from 700 to 950°C.

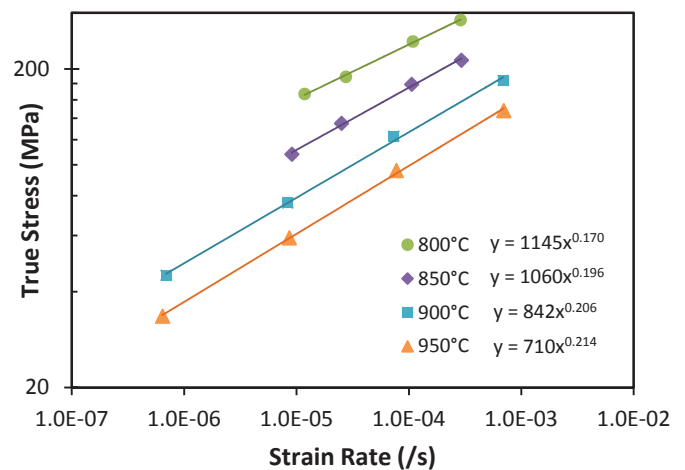


Fig. 5. Numerical fits to Equation 1 from strain rate jump tests over the temperature range 800 to 950°C for Alloy 617. The strain rate sensitivity parameter, m , is given in the exponent of the associated equations.

Strain rate jump tests for temperatures from 700 to 850°C for Alloy 800H are shown in Fig. 6. It can be seen that only for the temperature of 850°C are the increments in stress associated with the strain rate jump of consistent magnitude for all of the strain rates examined. At the two lower temperatures there is appreciable strain rate sensitivity at the low strain rates, but the magnitude of jumps decreases with increasing strain rate. As noted above the data for the 700°C test show evidence of negative strain rate sensitivity associated with the onset of serrated flow at the highest strain rate.(7) It is clear from Fig. 6 that the temperature for which there is insignificant strain rate sensitivity for Alloy 800H is being approached at 700°C for the higher strain rates.

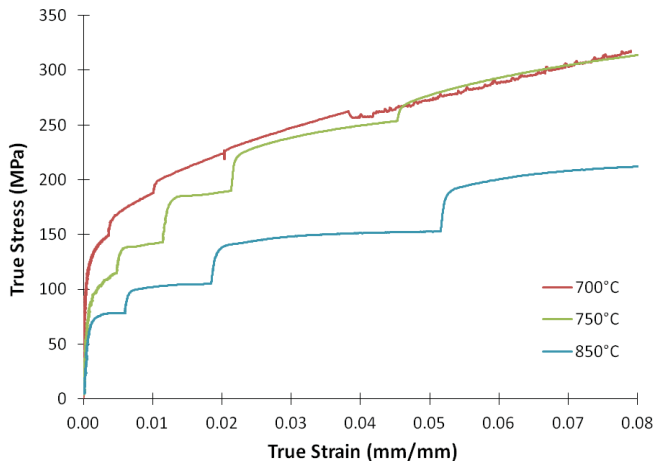


Fig. 6. Strain rate jump tests for Alloy 800H from at 700 to 850°C.

One additional jump test for Alloy 800H was carried out at 650°C and is shown in Fig. 7. This test was carried out in a slightly different test configuration and is not directly comparable to those in Fig. 6. It can be seen in this figure that there is slight negative strain rate sensitivity associated with serrated flow at several strain rates. There is little overall strain rate sensitivity at this temperature. Although negative strain rate sensitivity has been observed for austenitic stainless steels, (9) this is the first reported observation of this phenomena for Alloy 800H.

The strain rate sensitivity exponent of Alloy 617 fell in the range of 0.15 to 0.22 for all strain rates for temperatures above 750°C. Values for the strain rate sensitivity exponent of Alloy 800H as a function of strain rate are given in Table 1 for all of the test temperatures. It is apparent in the table that at 850°C Alloy 800H has behavior comparable to Alloy 617 tested above 750°C in that the value of m is relatively independent of strain rate. It appears that the temperature for which strain rate sensitivity is negligible for Alloy 800H (650°C) is approximately 50°C lower than for Alloy 617 (700°C).

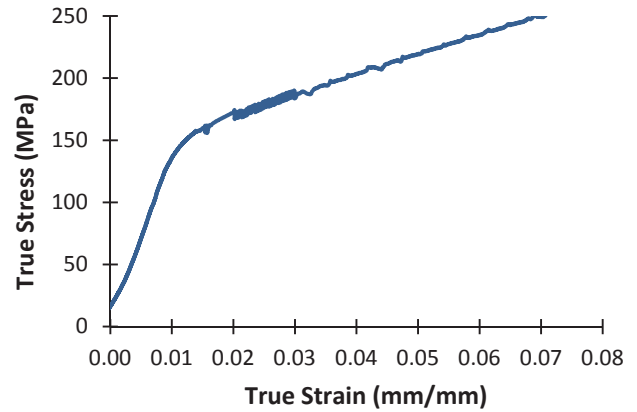


Fig. 7. Strain rate jump test for Alloy 800H at 650°C.

Table 1. Calculated values of the strain rate sensitivity exponent as a function of strain rate for Alloy 800H in the temperature range 650 to 850°C.

target strain rate jumps	temperature (°C)			
(/s)	650	700	750	850
7.00E-07 to 7.00E-06	-0.002	0.045	0.080	
7.00E-06 to 7.00E-05	-0.003	0.022	0.126	0.125
7.00E-05 to 7.00E-04	-0.009	0.006	0.085	0.157
7.00E-04 to 7.00E-03	-0.004	-0.014	0.035	0.147

The jump test results for both alloys at 850°C are plotted together in Fig. 8 to show the very similar qualitative behavior at this temperature. Data for Alloy 800H and 617 are shown for the 750°C test temperature in Fig. 9. Alloy 800H transitions from high m values at all strain rates to relatively low m values at high rates, over a 150°C range, while Alloy 617 exhibits little strain rate sensitivity at 750°C. It appears that the onset of serrated flow at this temperature results in a rather abrupt change in behavior for Alloy 617.

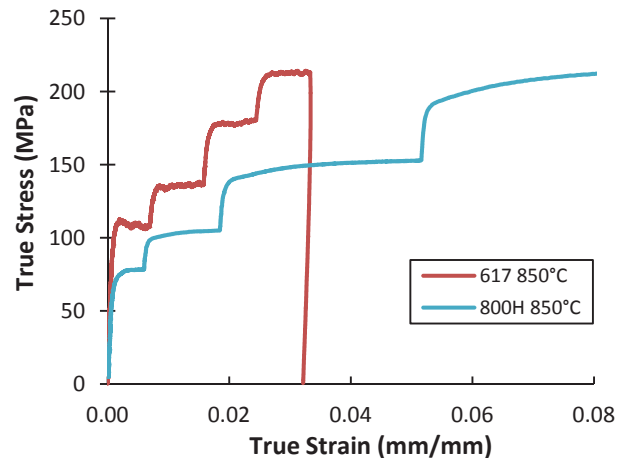


Fig. 8. Strain rate jump tests for Alloys 800H and 617 at 850°C.

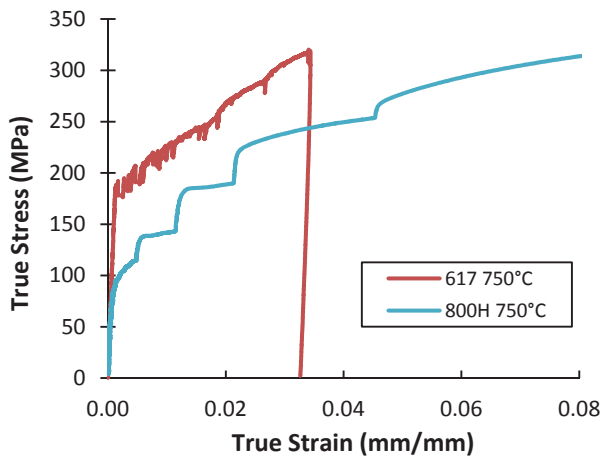


Fig. 9. Strain rate jump tests for Alloys 800H and 617 at 750°C.

Engineering stress strain curves for Alloys 617 and 800H as a function of temperature at a conventional initial strain rate for tensile tests of about 10^{-4} /s are shown in Figs 10 and 11, respectively. It appears that the temperature at which the alloys clearly transition to consistent rate sensitivity with high m values is the same as that for which the material ceases to exhibit work hardening in the tensile test, approximately 800°C for Alloy 617 and 750°C for Alloy 800H. This 50°C temperature increment correlates with the difference in temperature for which negligible strain rate sensitivity is observed. In each case serrated flow is observed about 150°C below this temperature.

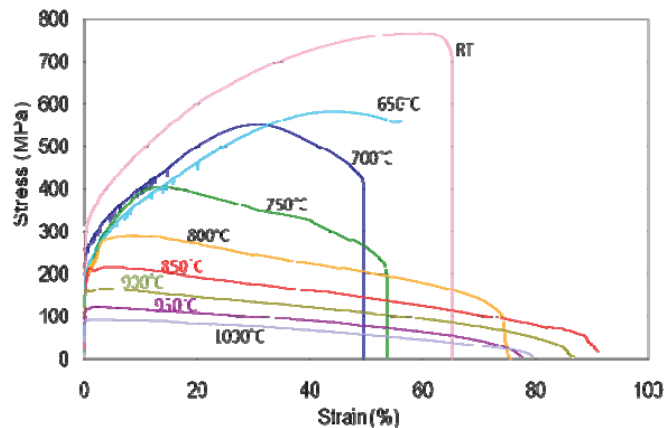


Fig. 10. Tensile stress strain curves for Alloy 617 as a function of temperature for a nominal strain rate of 10^{-4} /s.

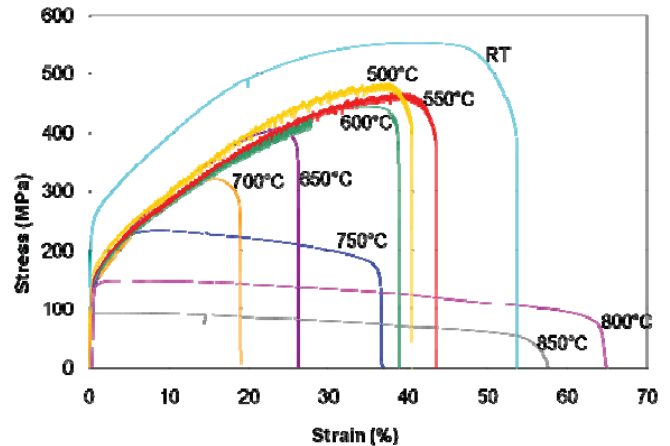


Fig. 11. Tensile stress strain curves for Alloy 800H as a function of temperature for a nominal strain rate of 10^{-4} /s.

CONCLUSIONS

The strain rate sensitivity of Alloy 800H and Alloy 617 has been determined for a range of temperatures using strain rate jump tests. At temperatures of 850°C the strain rate sensitivity of the two alloys is similar and the strain rate sensitivity exponent is approximately 0.2. For Alloy 617 the temperature limit below which little or no strain rate sensitivity is observed is approximately 700°C. For Alloy 800H this temperature is approximately 650°C. The temperature at which the alloys clearly transition to consistent rate sensitivity with high m values is the same as that for which the material ceases to exhibit work hardening in the tensile test, approximately 800°C for Alloy 617 and 750°C for Alloy 800H.

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